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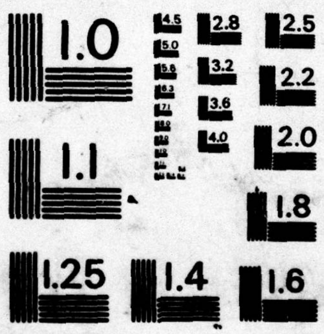

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THREE-DIMENSIONAL, GROSS-MOTION, CRASH-VICTIM SIMULATORS

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B. S.

INTRODUCTION

The past two decades have produced significant advances in hardware, software, and numerical methods. These advances have led to corresponding advances in finite element and finite segment modelling of mechanical systems. One of the most interesting and potentially useful areas of finite segment modelling is the gross motion simulation of the human body -- particularly the simulation of responses to crashes and high acceleration/impact environments. And, although advances in this area are directly related to advances in digital computer hardware and software, significant progress can also be attributed to new modelling approaches and more sophisticated computer coding of the models. Indeed, the technology has reached the point of being on the threshold of having several reliable, verified, well documented, user oriented models which can be used to accurately and efficiently predict the human response, and hence potential injury, for a variety of crash and high acceleration/impact configurations.

Currently there are as many as ten distinct gross motion simulators available including at least five three-dimensional models. Perhaps the first gross-motion simulator to be developed was a two-dimensional model advanced by McHenry [1] in 1963. This code was further developed and refined in subsequent years [2-5]. Other more recent two-dimensional simulators include those developed by Segal [5,6,7], Danforth and Randall [8], Glancy and Larsen [9], Karnes, Twigg, Tocher, et. al [10-13], and Robbins, Bennett, Bowman, et. al [14-17]. These simulators differ primarily in the variety of input-output options available. The three-dimensional simulators include those developed by Robbins, Bennett, Bowman, et. al (HSRI) [18-23], Young, et. al (TTI) [24,25,26], Laananen (SOM-LA) [27-30], Bartz, Fleck, et. al (CALSPAN) [31-36], and Huston, Passerello, et. al [37-41]. There is, of course, more diversity among these simulators because of their inherent complexity. It is the

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objective of this paper to provide a summary of the relative advantages, disadvantages, and ranges of application of these three-dimensional simulators.

The balance of the paper is divided into four parts with the first part containing a general discussion of the fundamentals of the modelling and the formulation of the codes. The second part provides a summary of the vital features of the simulators themselves. The third part provides a set of conclusions about the state-of-the-art together with recommendations regarding applications and uses of the codes, and the final part contains a condensed summary of the codes.

DEVELOPMENT OF A SIMULATOR

There are several major problem areas which need to be resolved before a crash-victim simulator is developed. First, a modelling of the human body and its surroundings (or cockpit) needs to be obtained. Even with the simplest codes, this involves thought, judgement, and approximation. With the more elaborate codes such as CALSPAN and UCIN, this can even involve soft tissue modelling, the inclusion of airbags, and other occupants.

The modelling of the human body leads in turn to the major problem of describing and accounting for the complex geometry of the model itself and its many possible configurations. Also, the problem of singularities and mathematically possible but physically impossible configurations, needs to be resolved.

Next, and perhaps most fundamental, governing dynamical equations of motion need to be formulated and written. There is still no apparent agreement among researchers about this. Some simulators, such as TTI, HSRI, and SOM-LA, use Lagrange's equations; CALSPAN uses a Newtonian approach; and UCIN uses a combination virtual-work type approach called Lagrange's form of d'Alemberts principle [42-45].

Following this, efficient algorithms need to be developed to program the governing equations into a computer code. This, in turn, involves finding a numerical integrator for the equations of motion. After this, documentation and users manuals need to be written so the code can be used by others. Indeed, this latter area is perhaps the major current area of interest of simulator researchers. It is probably the area which most needs to be developed.

Finally, a simulation code needs to be verified experimentally. It is extremely difficult to obtain reliable experimental data to check the codes. It has only been recently with the work of King, Ewing, et. al [46-50] that even the simplest kinds of experimental verification have been obtained. This area also still needs to receive attention by the researchers.

FIVE SPECIFIC SIMULATORS

In this part a summary of the major features of five of the most widely used and accepted gross-motion, crash-victim simulators (HSRI, TTI, SOM-LA, CALSPAN, and UCIN) is presented. These five were selected on the basis of their documentation in the literature, and their adoption by others, their continued development, and their experimental verification. This is not intended to imply that there are not other very useful and suitable three-dimensional human body models and codes available and under development. Indeed, the models of Furusho, Yokoya, et. al [51,52,53], Kane, et. al [54,55], Huston, Passerello, et. al [57-60], and Ghosh and Boykin [61] immediately come to mind. These are not specifically included because of either their limited degrees of freedom or because their development and application is not directed toward crash victim simulation.

The HSRI Model

This code was developed by Robbins, Bennett, Bowman, et. al [18-23] at the Highway Safety Research Institute of the University of Michigan (Ann Arbor, Mich. 48105). The model contains 6 mass segments providing 17 degrees of freedom. It contains both hinge and ball-and-socket type joints simulating the human joints. It has bilinear, unsymmetrical torsional springs at the joints with coupling between the pitch roll and yaw stops. There is provision for 4 seat-belt attachmetns to the torso of the model and forces are generated when the model strikes a cockpit intrusion surface. The motion input is via the cockpit with provision for piecewise-linear functions for as many as 6 (3 linear, 3 angular) cockpit accelerations. The governing equations are derived by using Lagrange's equations and they are numerically integrated using a Runge-Kutta, predictor-corrector method. The computer code is written in FORTRAN and it requires approximately 400K bytes of core memory.

The developers of this code had the objective of formulating an efficient, user-oriented, but yet comprehensive model. This necessitated a trade-off between the complexity (eg. degrees of freedom) of the model (and hence, its capability to accurately predict physical phenomena) and the economy of user and run time. The developers have apparently achieved a good balance between the two. The code (like most of the other codes) probably needs additional experimental verification.

The TTI Model

This code was developed by Young, et. al, [24,25,26] at the Texas Transportation Institute of Texas A & M University (College Station, Texas 77849). The model contains 12 mass segments providing 31 degrees of freedom. It has both hinge and ball-and-socket joints, simulating the human joints. It employs

bilinear viscous damping at the joints to simulate muscle and ligament forces. It has provision for lap and shoulder belt restraints and forces are generated when the model strikes a cockpit surface. The motion input is via the cockpit by specifing its linear and angular displacement as a function of time. Lagrange's equations are used to develope the governing equations and they are integrated numerically using a Runge-Kutta technique.

This code is perhaps more specialized than the other codes. That is, it is designed primarily for automobile crashes where the automobile displacement is known as a function fo time. Hence, it does not provide as much flexibility on input as some of the others. However, this allows the code to run more efficiently. Also, the viscous joint stops eliminate unwanted resonance characteristics which sometimes occur with spring stops. Finally, further experimental verification would be desirable.

The SOM-LA Model

This code was developed by Laananen [27-30], at the Dynamic Sciences Division of Ultrasystems, Inc. (1850 W. Pinnacle Peak Rd., Phoenix, Arizona 85027). The model contains 11 mass setments connected by hinge and ball-and-socket joints, simulating the human joints. It has 28 degrees of freedom. It employs nonlinear torsional springs and viscous dampers at the joints. It contains a finite element seat model and sliding lap and should belts. The motion input is via the seat with provision for 6 (3 linear, 3 angular) piecewise-linear acceleration functions. The governing equations are derived using Lagrange's equations and they are numerically integrated using a Runge-Kutta Adams-Moulton predictor-corrector method. The computer code is written in FORTRAN and it requires approximately 225K bytes of core memory.

The objective in the development of this model was to provide an aid in seat and restraint design as opposed to biodynamic research. Thus the model has the most elaborate seat and restraint modelling of all the codes. Some experimental verification with dummies has been obtained [30], but more is needed.

The CALSPAN Model

This code was developed by Fleck, Bartz, et. al [31-36] at the Transportation Research Department of the Calspan Corp. (Buffalo, N.Y. 14221). The model contains a variable number of mass segments (up to 20) with the standard version using 15. There may be either a null (locked), hinged, or ball-and-socket connection at each joint providing as many as 63 degrees of freedom. It has torsional and flexural spring and viscous joint moments to simulate muscle and ligament action. It employ extensible and sliding lap and shoulder restraint belts. It

has provision for contact forces generated when the model strikes an intrusion surface of the cockpit or when segments of the model strike each other. Air-bag force generation is also an option. The motion input is via the cockpit with provision for 6 (3 linear, 3 angular) piecewise-linear acceleration functions. It is also possible to accelerate the model by moving the cockpit surfaces onto the model. The governing equations are derived using Newton's laws and they are numerically integrated using a Runge-Kutta, predictor-corrector method. The computer code is written in FORTRAN and it requires approximately 500K bytes of core memory.

This model and its code are the most elaborate and complex of all the available codes. Indeed, probably far more effort and research has been expended in the development of this code than in any of the other codes. But, because of its complexity and its various options, it is probably the most difficult and expensive code to use. More user-oriented documentation is needed. There is probably more experimental verification of this code than the others, but more verification is still needed.

The UCIN Model

This code was developed by Huston, Passerello, et. al [37-41] at the University of Cincinnati (Cincinnati, Ohio 45221). The model contains 12 mass segments with a total of 34 degrees of freedom. It contains hinge and ball-and-socket joints simulating the human joints and a translation connection at the neck to simulate neck stretch. It has bilinear torsional and flexural viscous damping at the joints. It has provision for up to 10 restraint belts (modelled as linear springs) arbitrarily applied to the model. The motion input is via the cockpit with provision for 6 (3 linear, 3 angular) piecewise-linear acceleration functions. The computer code is written in FORTRAN and it requires approximately 120K bytes of core memory.

The principal feature of the UCIN code is its efficient development of the governing equations and its efficient computer algorithms. The governing equations are developed using a virtual work type principle called "Lagrange's form of d'Alembert's principle" which is claimed to have the advantages of both the Lagrangian and Newtonian approaches but without the corresponding disadvantages [42-45]. The governing equations are numerically integrated using a Runge-Kutta technique. This code is probably the simplest, most efficient, and easiest-to-use of all the codes, but it is also probably less specialized than most of the others. And, although the code has some good experimental verification, more is still needed.

CONCLUSIONS AND RECOMMENDATIONS

There are currently available a number of three-dimensional, gross-motion simulators which can provide a reasonable analytical computer simulation of human response to crash or high acceleration environments. Of the specific codes discussed here, none is probably in its final finished (or "ideal") form. Each of the codes needs more experimental verification. Each needs more user-oriented documentation and better user manuals. Better numerical integration routines and better soft tissue modelling is also needed.

It seems to be clear that one or more advanced versions of these codes should eventually take the place of dummies, cadavers, and much of the current experimental work. The general acceptance of the codes for such purposes by the researchers is, of course, dependent upon further experimental verification of the codes and the development of user-oriented documentation.

Although a comparison of the various codes has been made (See also the review papers King and Chou [62] and Robbins [63]), it is probably unfair to select a "best" code or "most useful" code since they have been developed with different end objectives. However, data which would be useful (in addition to more experimental verification) would be a comparison of the various codes using the same input data for a variety of crash configurations. Hopefully, such results will soon be forthcoming.

SUMMARY

The HSRI Model

Name: HSRI 3D
Developers: D. H. Robbins, R. O. Bennett, and B. M. Bowman
Highway Safety Research Institute
University of Michigan
Ann Arbor, Michigan 48105
Date: 1973
Objective: Efficient, comprehensive, user-oriented code
Degrees of Freedom: 17
Number of Mass Segments: 6
Language: Fortran IV
Hardware: IBM 360/370, Amdahl 470
Documentation and Verification: See References [18-23]
Availability: Contact D. H. Robbins at the above address.

The TTI Model

Name: TTI
Developer: R. D. Young
Texas Transportation Institute
Texas A & M University
College Station, Texas 77849
Date: 1970
Objective: Auto crash simulation
Degrees of Freedom: 31
Number of Mass Segments: 12
Language: Fortran IV
Hardware: IBM 360/370
Documentation and Verification: See References [24,25,26]
Availability: Contact R. D. Young at the above address.

The SOM-LA Model

Name: SOM-LA
Developer: D. H. Laananen
Dynamic Science Division
Ultrasystems, Inc.
1850 W. Pinnacle Peak Rd.
Phoenix, Ariz. 85027
Date: 1975
Objective: Seat and restraint simulation
Degrees of Freedom: Occupant-28, Seat-16
Number of Mass Segments: 11
Language: Fortran IV
Hardware: Univac 1108, CDC 6600
Documentation and Verification: See References [27-30]
Availability: Contact Ultrasystems at the above address.

The CALSPAN Model

Name: CAL3D
Developers: J. A. Bartz, J. T. Fleck, et.al.
Transportation Research Department
CALSPAN Corp.
Buffalo, N.Y. 14221
Date: 1972
Objective: Comprehensive crash-victim simulation
Degrees of Freedom: Variable (Up to 63)
Number of Mass Segments: Variable (Up to 20)
Language: Fortran IV
Hardware: IBM 360/370, CDC 6600
Documentation and Verification: See References [31-36]
Availability: Contact J. T. Fleck at the above address

The UCIN Model

Name: UCIN
Developers: R. L. Huston, C. E. Passerello, M. W. Harlow
Department of Engineering Science
University of Cincinnati
Cincinnati, Ohio 45221
Date: 1974
Objective: Comprehensive crash-victim simulation
Degrees of Freedom: 34
Number of Mass Segments: 12
Language: Fortran IV
Hardware: IBM 360/370, Amdahl 470
Documentation and Verification: See References [37-41]
Availability: Contact R. L. Huston at the above address

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